

Bosonic-Seesaw Portal Dark Matter

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We propose a new type of Higgs-portal dark matter-production mechanism, called bosonic-seesaw portal scenario. Bosonic seesaw provides the dynamical origin of the electroweak symmetry breaking, triggered by mixing between the elementary Higgs and a composite Higgs generated by a new-color strong dynamics (hypercolor) which dynamically breaks the classical-scale invariance of the model. The composite hypercolor-baryonic matter can then be a dark matter candidate, which significantly couples to the standard-model Higgs via the bosonic seesaw, and can be produced from the thermal plasma below the decoupling temperature around the new strong coupling scale, to account for the observed relic abundance of the dark matter: the dark matter can closely be related to the mechanism of the electroweak symmetry breaking.

Quarter of our universe is constituted by unknown matter, called the dark matter (DM). Several cosmological and astrophysical observations have so far suggested that the DM should be electrically neutral, cold enough and stable enough to be long-lived compared with the age of the universe. The abundance left in the present universe is thought to have been produced via interactions with the standard model (SM) particles in the early universe, involving so-called mediators such as the SM Higgs (Higgs portal scenario).

In this letter, we propose a new type of the Higgs-portal DM-production mechanism, which we call the bosonic-seesaw portal scenario. The DM candidate arises as a composite state of new fermions, strongly coupled in a new-color dynamics (hypercolor (HC)), which triggers the electroweak symmetry breaking (EWSB) via the seesaw, and hence *the relic abundance of the DM directly links to the EWSB*.

The scenario employed here is basically built by two sectors: one is a classically scale-invariant SM having no Higgs mass term, while the other is the HC sector, the vector-like gauge dynamics of $SU(N_{\text{HC}})$. As discussed in Refs [1–3], the HC fermions form bound states at around the strong scale Λ_{HC} , breaking the scale-invariance, in which a composite scalar doublet, having the same quantum numbers as those of the SM Higgs doublet, can be present. Then, mixing between those two Higgs doublets can be generated through couplings to the SM gauge bosons at the loop level [3], or the SM fermions at the tree-level [1, 2]. The mixing strength (coupling) is thus small enough to yield the (square of) mass matrix between two Higgs doublets in the seesaw type form like

$$\begin{pmatrix} 0 & y\Lambda_{\text{HC}}^2 \\ y\Lambda_{\text{HC}}^2 & \Lambda_{\text{HC}}^2 \end{pmatrix}, \quad (1)$$

with the mixing strength $y \ll 1$. Note that the determinant of the mass matrix is negative, so the negative mass-squared of the SM Higgs is dynamically generated by the seesaw mechanism (bosonic seesaw [4]) to trigger the EWSB.

In addition to the composite Higgs, the HC sector generically involves the rich composite spectra such as the HC pions and baryons as in the case of QCD. Among those HC hadrons, some of HC baryons can be stable due to the conserved HC baryon number, hence can be a DM candidate. Our main claim in the present paper is that the HC baryon with the mass of $\mathcal{O}(\text{TeV})$ ^{#1} can indeed be the DM and *the DM relic abundance is closely related to the mechanism of the EWSB*.

To demonstrate the point, as a concrete example we shall take a model of the bosonic seesaw discussed in Refs. [1, 2]. In the model we introduce the HC fermions ψ and χ respectively having the charges $(1, 1, 0, N_{\text{HC}})$ and $(1, 2, 1/2, N_{\text{HC}})$ under the $SU(3)_c \times SU(2)_W \times U(1)_Y \times SU(N_{\text{HC}})$ gauge groups. The HC fermions couple to the elementary Higgs doublet H as $y\bar{\chi}H\psi$. At around the scale Λ_{HC} , a composite Higgs doublet Θ , having the mass of $\mathcal{O}(\Lambda_{\text{HC}})$, is generated as $\Theta \sim \bar{\psi}\chi$. This Θ mixes with the elementary Higgs doublet H , through the above Yukawa term, like $yH^\dagger\Theta$, yielding the mixing mass matrix as in Eq.(1) to trigger the EWSB.

We now suppose that the HC sector possesses $N_{\text{HC}} = 4$, i.e. the $SU(4)_{\text{HC}}$. The HC baryon can be realized as a complex scalar, having the HC scalar-baryon charge. (Our argument is substantially unchanged even if we employ the case other than the $SU(4)_{\text{HC}}$ in which fermionic HC baryons can be present.) Among them, the EW-singlet HC scalar-baryon, $\varphi \sim \psi\psi\psi\psi$ can be a DM candidate which is stabilized by the HC-baryon conserved

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^{#1} In Ref. [3] the relic abundance produced by the HC sector has been estimated so that the HC baryon mass is required to be of $\mathcal{O}(100)$ TeV, so as to be consistent with the correct abundance of the DM.

charge. The mass is expected to be on the order of $\mathcal{O}(N_{\text{HC}}\Lambda_{\text{HC}})$. (In the Refs. [5], a similar composite dark baryon as the DM candidate, so-called stealth DM, has been discussed in a context different than the bosonic seesaw.)

The scale $\Lambda_{\text{HC}} \simeq m_\varphi$ can be set by considering the bosonic seesaw relation derived so as to realize the EWSB, $\lambda_\Theta v^2 \simeq \Lambda_{\text{HC}}^2$ [2], with the EW scale $v \simeq 246$ GeV. Here λ_Θ denotes the quartic coupling of the composite Higgs doublet Θ , the size of which can be estimated, in a way analogous to the linear sigma model of QCD, to be $\lambda_\Theta = \mathcal{O}(10^{2-3})$. (Recall the QCD sigma meson mass, on the order of GeV, is expressed by the linear sigma model as $m_\sigma \sim \sqrt{\lambda_\sigma} f_\pi$ with the QCD pion decay constant $f_\pi \sim 100$ MeV and the quartic coupling λ_σ . From this relation we find $\lambda_\sigma \sim 100$.) Hence the Λ_{HC} is expected to be of $\mathcal{O}(\text{TeV})$.

The φ , the EW-singlet complex scalar baryon, strongly and minimally couples to the composite HC Higgs doublet, Θ , like

$$a \cdot \varphi^\dagger \varphi \Theta^\dagger \Theta, \quad (2)$$

with the order one (or larger) coefficient a . By the bosonic seesaw mechanism, the Θ starts to mix with the elementary Higgs doublet H below the scale Λ_{HC} . This dynamically generates, so-called, a Higgs portal coupling

between the dark matter φ and the SM Higgs H_1 :

$$\kappa_{\varphi H} \cdot \varphi^\dagger \varphi H_1^\dagger H_1, \quad \text{with} \quad \kappa_{\varphi H} = ay^2, \quad (3)$$

where the factor y^2 has come from the bosonic-seesaw mixing strength y ($\Theta \approx yH_1 + H_2$, which can be understood by diagonalizing the mass matrix Eq.(1)) between the SM Higgs H_1 and heavy Higgs H_2 . The mixing strength y is supposed to be much smaller than $\mathcal{O}(1)$, so that the Higgs portal coupling $\kappa_{\varphi H}$ can naturally be small to be consistent with the present relic abundance of the dark matter, as will be clarified later on.

In the thermal history, the HC scalar-baryon φ was decoupled from the thermal equilibrium at the temperature around Λ_{HC} because of the decoupling of the HC pions and HC fermions. Crucial to note is, however, that since the φ has the Higgs portal coupling in Eq.(3), dynamically induced from the bosonic seesaw, the φ can still be thermally produced via the SM sector below the decoupling temperature $T = \Lambda_{\text{HC}}$, a la “freeze-in” scenarios.

Thus, we evaluate the thermal production cross sections arising from the bosonic-seesaw portal coupling in Eq.(3). Below $T = \Lambda_{\text{HC}}$, the relevant processes are: $hh, t\bar{t}, WW, ZZ \rightarrow \varphi^\dagger \varphi$. Those cross sections are computed at the tree-level of the perturbation in couplings to be

$$\begin{aligned} \sigma(hh \rightarrow \varphi^\dagger \varphi) &= \frac{\kappa_{\varphi H}^2}{16\pi} \frac{s}{(s - m_h^2)^2} \left(1 - \frac{4m_\varphi^2}{s}\right)^{5/2}, \\ \sigma(WW/ZZ \rightarrow \varphi^\dagger \varphi) &= \frac{9\kappa_{\varphi H}^2}{64\pi} \frac{s}{(s - m_h^2)^2} \left(1 - \frac{4m_\varphi^2}{s}\right)^{1/2} \left(\frac{m_{W/Z}^2}{s}\right)^2 \left[2 + \left(1 - \frac{s}{2m_{W/Z}^2}\right)^2\right], \\ \sigma(t\bar{t} \rightarrow \varphi^\dagger \varphi) &= \frac{3\kappa_{\varphi H}^2}{32\pi} \frac{s}{(s - m_h^2)^2} \left(1 - \frac{4m_\varphi^2}{s}\right)^{1/2} \left(\frac{m_t^2}{s}\right) \left[1 - \frac{4m_t^2}{s}\right], \end{aligned} \quad (4)$$

with \sqrt{s} being the center of mass energy. The number density per entropy density today, $Y(T_0) = n(T_0)/s(T_0)$,

can be calculated by integrating the Boltzman equation with the production cross sections $\sigma(ij \rightarrow \varphi^\dagger \varphi)$ to be

$$Y(T_0) = \frac{135\sqrt{10}M_p\zeta^2(3)}{32\pi^7} \int_{T_0}^{\Lambda_{\text{HC}}} dT \sum_{i,j} \frac{g_i g_j \eta_i \eta_j}{[g_*(T)]^{3/2}} \int_0^\infty dx x^4 K_1(x) \sigma(ij \rightarrow \varphi^\dagger \varphi), \quad (5)$$

where $g_*(T)$ stands for the effective degree of freedom for relativistic particles, $g_i = 2(1)$ and $\eta_i = 3/4(1)$ for fermions (bosons), $M_p \simeq 10^{18}$ GeV (reduced Planck mass), $K_1(x)$ denotes the modified Bessel function of the

first kind, $\zeta(3) \simeq 1.202$, $x \equiv \sqrt{s}/T$ and T_0 is the temperature at present.

The thermal-relic abundance, $\Omega_\varphi h^2 = Y(T_0) \cdot m_\varphi s(T_0)/(\rho_{\text{cr}} h^{-2})$, turns out to actually be almost in-

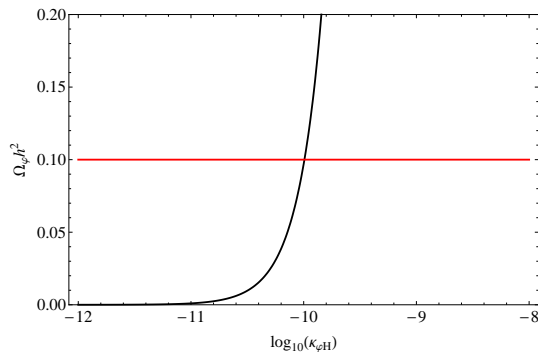


FIG. 1: The constraint on the bosonic-seesaw portal coupling $\kappa_{\phi H}$ from the presently observed relic abundance ($\simeq 0.1$ drawn as red-horizontal line in the plot). The dependence of dark matter mass is almost negligible in evaluating the relic abundance. The plot has been shown by taking the mass to be 1 TeV.

dependent of the ϕ mass. The bosonic-seesaw portal coupling $\kappa_{\phi H}$ is then constrained by the presently observed dark matter abundance $\simeq 0.1$. Figure 1 shows the constraint plot on the portal coupling, which shows us

$$\kappa_{\phi H} \lesssim 10^{-10}, \quad \text{or} \quad y \lesssim 10^{-5} \times (1.0/a)^{1/2}, \quad (6)$$

where $g_*(T)$ in Eq.(5) has been taken to be $\simeq 100$. The smallness of the portal coupling is consistent with the bosonic seesaw mechanism: the small portal coupling, required by the relic abundance, can naturally be encoded in the bosonic seesaw scenario. Note also that the tiny $\kappa_{\phi H}$ or y in Eq.(6) is consistent with the bosonic seesaw paradigm.

Having the Higgs portal coupling, the HC scalar-baryon dark matter can be detected by the direct detection experiments such as the LUX [6], PandaX-II [7], and upcoming XENON1T and LZ [8]. The spin-independent

(SI) cross section is computed as $\sigma_{SI}(\phi N \rightarrow \phi N) \simeq \frac{\kappa_{\phi H}^2}{16\pi m_h^4} m_*^2(N, \phi) g_{hNN}^2$, where $g_{hNN} \simeq 0.25 \text{ GeV}/v$ [9–11] and $m_*(N, \phi) = m_N m_\phi / (m_N + m_\phi)$ is the reduced mass with $m_N \simeq 940 \text{ MeV}$. Using the upper bound for the portal coupling $\kappa_{\phi H}$ in Eq.(6) and taking the dark matter mass 1-5 TeV for the reference value, we find the upper bound on the SI cross section, $\sigma_{SI} \lesssim 10^{-63} \text{ cm}^2$. This value is far below the current limit most stringently set by the LUX2016 [6], and the sensitivity in the future-prospected XENON1T or LZ, $\sigma_{SI} \leq 10^{-47} \text{ cm}^2$ at the TeV range [8], which will actually be overlapped with the expected neutrino background [12].

In conclusion, the bosonic-seesaw portal scenario, proposed in the present paper, provides a dark matter candidate having the coupling to the standard model Higgs, which is dynamically generated by the seesaw and essentially related to the origin of the electroweak symmetry breaking. In this scenario the dark matter, having the mass of TeV scale, dynamically arises as the hypercolor baryon with the conserved hypercolor-baryon charge, and the thermal relic abundance can be produced enough due to the significantly small coupling to the standard model Higgs as the consequence of the bosonic seesaw mechanism, namely, the electroweak symmetry breaking. Since having the extremely small portal coupling, the bosonic-seesaw portal dark matter is fairly insensitive to the direct detection experiments, which would imply other detection proposals.

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